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The Nature of Lyman Break Galaxies in Cosmological Hydrodynamic Simulations

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Abstract. What type of objects are being detected as $z \sim 3$ "Lyman break galaxies"? Are they predominantly the most massive galaxies at that epoch, or are many of them smaller galaxies undergoing a short-lived burst of merger-induced star formation? We attempt to address this question using high-resolution cosmological hydrodynamic simulations including star formation and feedback. Our ΛCDM simulation, together with Bruzual-Charlot population synthesis models, reproduces the observed number density and luminosity function of Lyman break galaxies when dust is incorporated. The inclusion of dust is crucial for this agreement. In our simulation, these galaxies are predominantly the most massive objects at this epoch, and have a significant population of older stars. Nevertheless, it is possible that our simulations lack the resolution and requisite physics to produce starbursts, despite having a physical resolution of $\lesssim 700$ pc at $z = 3$. Thus we cannot rule out merger-induced starburst galaxies also contributing to the observed population of high-redshift objects.

1. Introduction

The detection of large numbers of high-redshift galaxies using the Lyman break technique has greatly furthered our understanding of early galaxy formation. A variety of arguments, from clustering[1] to semi-analytic modeling[2] to N-body simulations[3], suggest that these Lyman break galaxies (LBGs) form in

highly biased, rare density peaks in the early universe. However, the nature of these galaxies remains controversial. Are they the most massive galaxy contained in these peaks, having quiescently formed stars for some time[4]? Or are they smaller galaxies residing in large potential wells that are undergoing an short-lived merger-induced starburst[5]? The key to answering this question is to determine the mass of the underlying galaxy. This may be done observationally[6] or by modeling processes of galaxy formation[7]. So far, only N-body and semi-analytic techniques have been applied, and the results vary, depending primarily on what is assumed for merger-induced starbursts. In principle, hydrodynamic simulations of galaxy formation including star formation, together with population synthesis models, can directly address these questions within a given cosmology. That is what we investigate in these proceedings.

2. Simulation and Analysis

We simulate a random $11.111h^{-1}$Mpc cube in a ΛCDM universe, with $\Omega_m = 0.4$, $\Omega_\Lambda = 0.6$, $H_0 = 65$, $n = 0.95$, and $\Omega_b = 0.02h^{-2}$. We use Parallel TreeSPH to advance 128^3 gas and 128^3 dark matter particles from $z = 49$ to $z = 3$. Our spatial resolution is $1.7h^{-1}$ comoving kpc (equivalent Plummer softening), implying that at $z = 3$ our physical resolution is ~ 640pc. Our mass resolution is $m_{SPH} = 1.3 \times 10^7 M_\odot$ and $m_{dark} = 1 \times 10^8 M_\odot$. Using a 60-particle criterion for our simulated galaxy completeness limit[8] implies that we are resolving most galaxies with $M_{baryonic} \gtrsim 8 \times 10^8 M_\odot$.

We include star formation and thermal feedback[9]. At $z = 3$, we identify galaxies using Spline Kernel Interpolative DENMAX (SKID), and compile a list of star formation events in each galaxy. Since gas is gradually converted into stars in each SPH particle, a given particle can have up to 20 star formation events. We treat each event as an instantaneous single-burst population using Bruzual & Charlot's GISSEL98[10], assuming a Scalo IMF with $Z = 0.4Z_\odot$[1]. We sum the spectra for all events in a galaxy to produce its rest-frame spectrum at $z = 3$. We apply a correction for dust absorption using a galactic extinction law[11] with $A_V = 1.0$. We then redshift the spectra to $z = 0$ and apply U_nGR filter functions[12] to obtain the observed broad-band colors for our simulated galaxy population. Note that no K-correction is necessary since we redshift the spectrum prior to applying the filters.

3. The Simulated Lyman Break Galaxy Population

Our simulation produces 1238 galaxies at $z = 3$. Figure 1 shows the luminosity functions Φ in R (solid histogram), G (dotted line) and U_n (dashed line) of these galaxies. Note that $\Phi(U_n)$ is shown without any attenuation due to HI along the line of sight. The left and right panels show Φ without and with dust, respectively. The turnover above $R \gtrsim 28$ is likely due to resolution effects, while the lack of galaxies with $R \lesssim 24$ is due to our small volume. Between

[1] Using a Salpeter or Miller-Scalo IMF results in more LBGs. However, dust plays a larger role in determining galaxy properties.

these values, our luminosity function (with dust) is in rough agreement with the observed R-band luminosity function [13], shown as the solid curve down to $R = 27$ (the current observational limit), although somewhat steeper. In reality, there is probably a range of dust extinctions, and this will tend to flatten Φ.

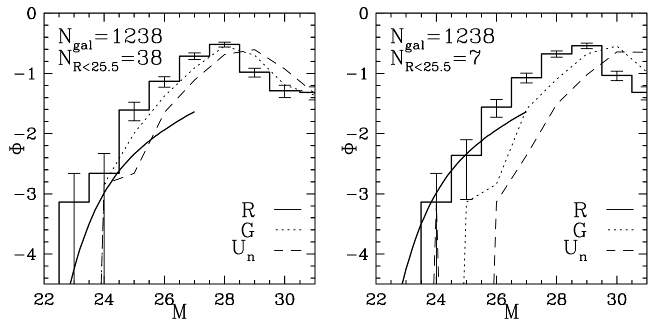

Figure 1: Luminosity function of high-redshift galaxies in U_n, G and R, without (left panel) and with (right panel) dust.

The number of Lyman break galaxies expected for this cosmology and volume is ~ 7 [1,13], though this number could be higher due to source confusion [15]. With dust included, we produce 7 galaxies with $R < 25.5$, of which 6 satisfy the LBG color selection, in reasonable agreement with observations. Without dust, there are 38. Not surprisingly, the number density of simulated LBGs is highly sensitive to the amount of dust included, and undoubtedly to the type and distribution of dust as well.

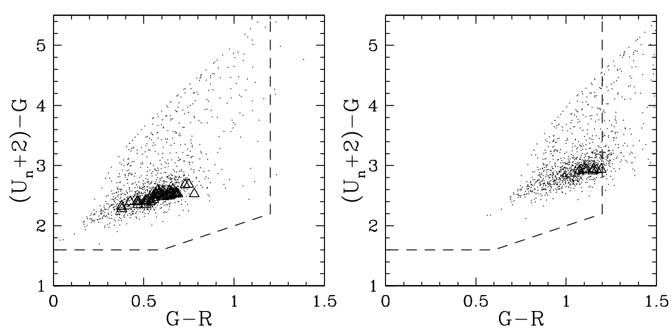

Figure 2: $(U_n + 2) - G$ vs. $G - R$ of simulated galaxies, without (left panel) and with (right panel) dust. Triangles have $R < 25.5$, dots have $R > 25.5$.

Color selection is at the heart of the Lyman break technique. In Figure 2 we show $U_n - G$ vs. $G - R$ plots of our simulated galaxies, with an arbitrary two magnitudes of extinction added to U_n to crudely mimic intervening HI absorption. Triangles represent galaxies with $R < 25.5$, and dots are the remaining galaxies. The Lyman break color selection is up and to the left of the dashed boundary. Left and right panels show without and with dust, respectively. Dust moves galaxies to higher $G - R$, and somewhat higher $U_n - G$. Most galaxies at $z = 3$ fall within the color selection, but significantly more dust would move the bright galaxies outside the $G - R < 1.2$ criterion.

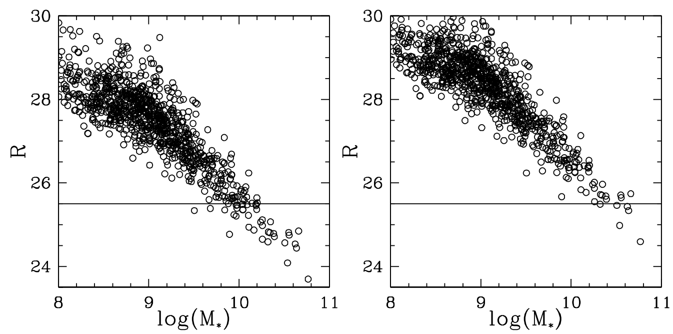

Figure 3: Stellar mass vs. R, without dust (left panel) and with dust (right panel).

We now investigate the mass of simulated LBGs. Figure 3 shows the stellar mass vs. R-band magnitude. The horizontal line demarcates $R = 25.5$, the magnitude limit of the observed LBG sample. While there is some scatter, the clear trend is that the brightest objects are also the most massive ones. The scatter increases to smaller masses, and is slightly larger in G and U_n, but our simulations indicate that LBGs are the most massive galaxies at $z = 3$.

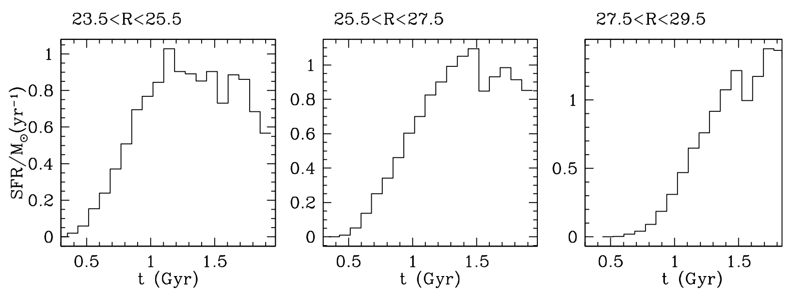

Figure 4: Star formation rate per unit stellar mass as a function of time (age of the universe), in three different R-band magnitude ranges.

Figure 4 shows the evolution of the star formation rate per solar mass of stars for three galaxy samples: $R < 25.5$ (left panel), $25.5 < R < 27.5$ (middle panel), and $27.5 < R < 29.5$ (right panel). The brightest galaxies have been forming stars the longest, typically for over a Gyr by $z = 3$. Thus they contain a significant older stellar population. Fainter (and smaller) galaxies have formed the bulk of their stars more recently.

4. Conclusions

Our simulation roughly reproduces the number density and luminosity function of LBGs for a reasonable value of dust extinction. It suggests that LBGs are the most massive objects at $z \sim 3$, and that they contain a significant older stellar population.

While this simulation puts forth a consistent picture for the nature of LBGs, we cannot rule out the aforementioned alternative scenario that LBGs are smaller starbursting galaxies. The reason is that starburst regions are typically a few hundred parsecs across, and therefore below our resolution. The star formation rate in our simulations is tied primarily to the local density (using a

Schmidt Law) which is limited by resolution. Thus we do not effectively mimic "starbursts" as would occur in a much higher resolution merger simulation[14]. Conversely, some semi-analytic models insert such starburst behavior explicitly, so it is not surprising that they obtain different results.

At present, it is not feasible to run simulations of sufficient resolution to resolve starbursts while still modeling a random cosmological volume. Furthermore, starbursts are likely to be governed by many other physical processes that we are only crudely modeling at present, such as feedback and ionization. Thus we cannot rule out the possibility that smaller starbursting systems also contribute to the observed Lyman break galaxy population. Nevertheless, our simulation with reasonable physical parameters is able to reproduce the basic observed properties of this population without including such objects.

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